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Funds were received in April 2001 under the Department of Defense DURIP program for construction of a 48 processor high performance computing cluster. This report details the hardware which was purchased and how it has been used to enable and enhance research activities directly supported by, and of interest to, the Air Force Office of Scientific Research and the Department of Defense. The report is divided into two major sections. The first section after this summary describes the computer cluster, its setup, and some cluster performance benchmark results. The second section explains ongoing research efforts which have benefited from the cluster hardware, and presents highlights of those efforts since installation of the cluster.

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Computing Cluster for Large Scale Turbulence Simulations and Applications in Computational Aeroacoustics

DoD DURIP Grant F49620-01-1-0239
Technical summary of computer cluster construction and use
during the period 3/31/01 through 3/31/02.

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1 Summary

Funds were received in April 2001 under the Department of Defense DURIP program for construction of a 48 processor high performance computing cluster. This report details the hardware which was purchased and how it has been used to enable and enhance research activities directly supported by, and of interest to, the Air Force Office of Scientific Research and the Department of Defense. The report is divided into two major sections. The first section after this summary describes the computer cluster, its setup, and some cluster performance benchmark results. The second section explains ongoing research efforts which have benefited from the cluster hardware, and presents highlights of those efforts since installation of the cluster.

2 Cluster Construction and Benchmarking

The original proposal requested funds for 24 dual-processor computing nodes along with a high bandwidth interconnect and other supporting hardware. The author was able to combine the granted DURIP funds with funds from an independent research grant awarded to investigators in the Chemical Engineering and Mechanical Engineering departments at Stanford University, and build a larger machine which met the needs of both groups. This combination of funding allowed for price/performance ratio benefits through economy of scale and bulk order pricing. The result was "whitehot," a rack mounted, 112 processor, high performance computing cluster, shown in Figure 1. The DURIP project group maintains control and exclusive use of 48 of the available processors, with the balance of resources allocated to the collaborating group.

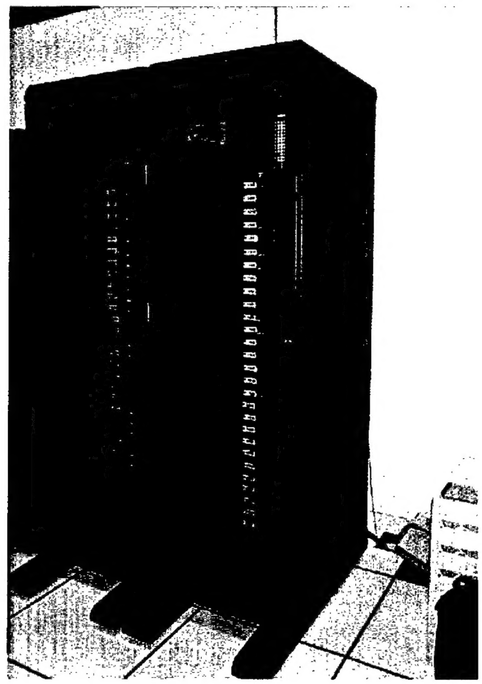

Figure 1: Photograph of the 56 node rack mounted cluster, named "whitehot."

Qty	Component
1	Penguin Computing Niveus Full Tower Server
56	Penguin Computing Relion 110 Dual Pentuin III 1 Ghz Compute Node
56	Dolphin Wulfkit 64bit/66MHz PCI adaptor card
56	Serial, Ethernet, and Dolphin Cable Kit
5	APC Vertical Mount Power Distribution Unit
2	Cyclades 32 Port Terminal Server
2	42U Enclosure with Ceiling Fans
1	Intel Express 530T 72 Port Fast Ethernet Switch

Table 1: Hardware list for the purchased cluster configuration.

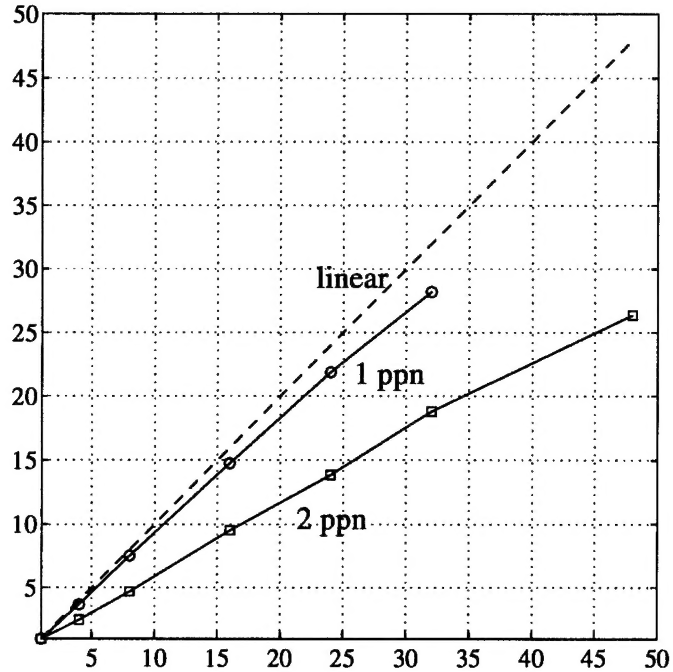

Figure 2: DNS benchmark problem results for one process per node (1 ppn) and two processes per node (2 ppn).

Several hardware vendors were considered before the final decision was made to purchase from Penguin Computing in late May 2001. The hardware for the entire purchased cluster configuration is shown in Table 1. Each compute node contains two 1 GHz Pentium III processors, 1 Gbyte of PC133 RAM, and a 30 GB EIDE hard disk, giving a cluster theoretical peak performance of 112 gigaflops. Internode communication is handled by Dolphin Wulfkit 64 bit/66 MHz PCI cards installed in each of the nodes. The Dolphin PCI cards are connected via special cables in a two dimensional torus topology. The Dolphin Wulfkit system is capable of providing interprocess bandwidth in excess of 150 Mbyte/sec for point-to-point communication using the message passing interface (MPI) software layer. The master node is a dual processor Pentium III machine which contains a total of 290 Gbytes of local hard disk space. A local fast ethernet network connected by an Intel Express 530T rack-mounted switch provides an additional communication layer for system maintenance, system monitoring, and user access. System hardware is covered by two years of replacement coverage and onsite support.

All hardware was installed and originally configured by Penguin Computing. Penguin also installed the Linux operating system, Scali cluster management software, the Scali MPI implementation, and the OpenPBS queue management system. Software added after the initial setup included the Portland Group FORTRAN 77 and Fortran 90 compilers as well as the BLAS, LAPACK, and FFTW math libraries. The hardware setup was completed by 27 July 2001, with software installation, cluster testing and benchmarking taking place during the month of August 2001. Figure 2 shows the results from a benchmark test consisting of a number of calls to a routine which constructs a numerical approximation to the spatial terms appearing in the compressible Navier-Stokes equations. The computations performed in this benchmark are typical of the calculations required during a high fidelity direct numerical simulation of an unsteady fluid flow. Speedup for

this benchmark was nearly linear for one process per node calculations. When two processes per node where used, performance per processor dropped by about 30-35% due to PCI and memory bus sharing between processes. However, this performance penalty is offset by the network and enclosure cost savings inherent in a dual processor cluster design.

3 Cluster Applications

High Speed Turbulent Jets

The suppression of noise produced by the exhaust gases from high thrust jet engines continues to be an important issue for civil and military applications. The Federal Aviation Administration has set stringent 'Stage 3' noise requirements on new commercial aircraft entering service and is planning for the even more stringent 'Stage 4' noise requirements. To aid in the new technology needed for this noise suppression NASA has begun aircraft noise research programs to reduce aircraft noise by 10 dB by 2007 and by 20 dB by 2022. In military applications, shock-associated jet noise has been found as a source of structural fatigue in the aft sections of fighter aircraft. One particular example is the damage to the tail sections of F-15s caused by jet screech, a discrete component of shock-associated jet noise.

The hardware provided through the DURIP funds directly supports research to understand the physics of the noise produced by sub- and supersonic jets. One such project is the numerical simulation of a Mach 0.9 turbulent jet by large eddy simulation (LES), whose goal is to define the state-of-the-art in LES predictions of jet noise. By determining the capabilities and limits of LES in noise predictions, a design and engineering tool is made available that, to date, has not existed in industry. The high fidelity predictions are able to be completed in a reasonable amount of time (relative to the typical design cycle) such that design-relevant trends are able to be determined.

A typical example is shown in Figure 3 where the sound from a turbulent jet is clearly shown. Using the information available in a numerical simulation, the noise from the jet can be extrapolated to an observer far away from the jet in a manner that more realistically represents the actual design problem. These results were obtained from a numerical calculation of approximately three weeks in length using 32 processors and the Message Passing Interface (MPI). More detailed investigation is desired in an effort to locate the physical mechanisms of noise generation and relate them to possible design changes but is currently prohibited by the limited amount of storage space available for the time dependent three dimensional flow fields needed.

Shock-associated noise prediction work is also being facilitated by the DURIP-provided computer cluster. In this work, the ability of LES to predict the broadband shock-associated noise is being tested by comparison with available direct numerical simulation (DNS) data. Results from the research, of which a portion were reported in Bodony and Lele (2002), are being used to improve the quality of noise predictions through the development of new subgrid scale models in the LES formulation. Improved models developed in this work will be re-applied to the aforementioned turbulent jet noise problem.

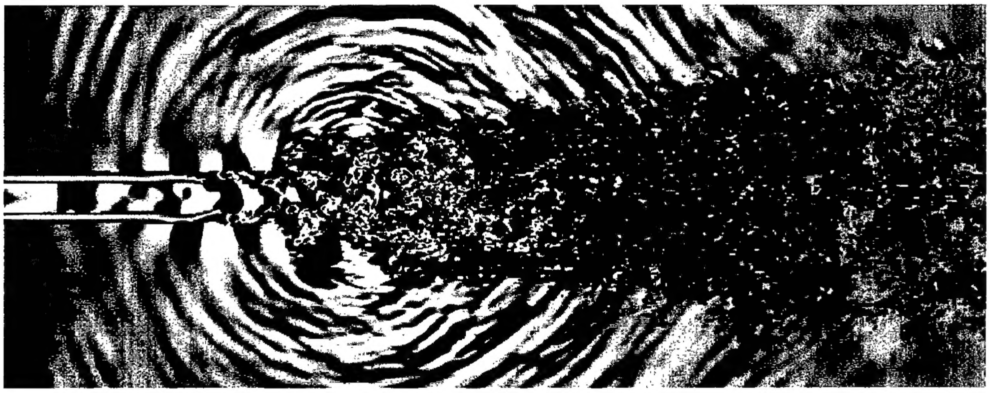

Figure 3: Flowfield snapshot from LES of a turbulent jet, showing turbulent vorticity fluctuations in the jet (colors) creating acoustic waves which radiate to the farfield (greyscale).

Large Eddy Simulation of Turbine Blade Heat Transfer

Performance of gas turbine engines is limited in a fundamental way by the maximum allowable turbine inlet temperature, which is related to the efficiency of individual turbine blade heat transfer characteristics. The objective of this research is to develop large eddy simulation (LES) as a tool for heat transfer prediction over a turbine blade immersed in a hot stream containing free-stream turbulence (FST).

Recent progress in algorithm development has been made in applying LES to this problem, particularly in the areas of specification of realistic free-stream turbulence in the computational inflow region, and in development of efficient numerical schemes for LES at the desired flow conditions. One set of computations completed to date explores heat transfer characteristics in the leading edge region of a turbine blade with oncoming FST. Figure 4 show snapshots of instantaneous heat transfer rate on the elliptic leading edge surface, which is viewed from an oblique head-on angle. This calculation required a mesh of 191 by 144 by 48 grid points over a domain of size $3.3D$ by $5.0D$ by $0.4D$, where D is the leading edge diameter of curvature. The free stream Mach number is $M_\infty = 0.15$, the FST intensity is $u'_\infty/U_\infty = 0.06$, and the Reynolds number is $Re_D = 42000$. Details of the numerical method used in this calculation were reported in Xiong and Lele (2001); the code executes in parallel and runs efficiently on the DURIP computing cluster. Figure 5 shows the good agreement obtained between the LES and the experiment of Van Fossen et. al. [1], performed at the same flow conditions and with the same geometry as the computation.

Computational results such as those shown in Figure 4 are being used to enhance understanding of the dynamic processes important in leading edge heat transfer in the presence of turbulence. For example, in the figure, regions of enhanced heat transfer appear as broad streaks on the wall. These streaks are associated with FST eddies which are stretched as they near the leading edge. Observations such as these have led to a new theoretical analysis of the impact of stretched FST eddies on the wall heat transfer in a stagnation point boundary layer, detailed in Xiong and Lele (2002).

Figure 4: Snapshots of instantaneous heat transfer rate on a turbine blade leading edge surface.

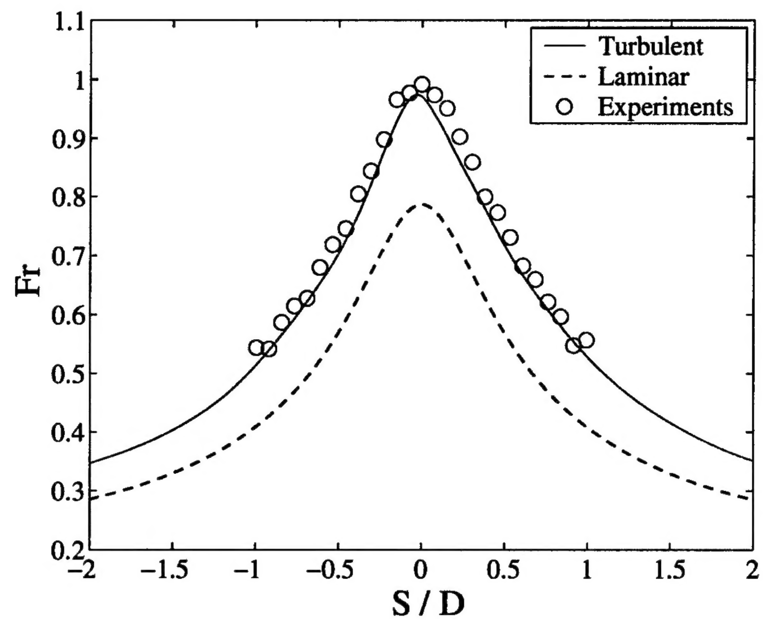

Figure 5: Comparison of the surface distribution of heat transfer (Fr = Frossling number) for laminar and turbulent calculations, versus experiment.

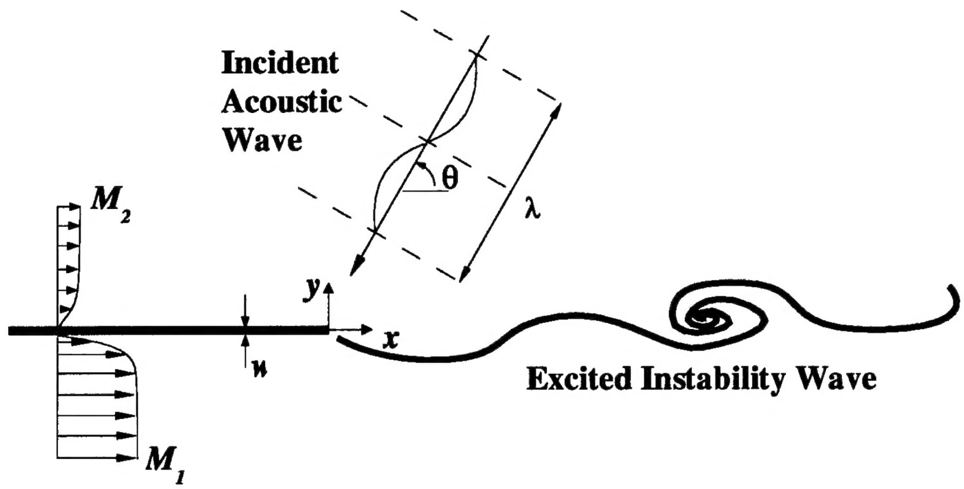

Figure 6: Schematic of the mixing layer receptivity computation.

Computation of Mixing Layer Receptivity

Excitation of shear flows by sound is an important element in naturally occuring aeroacoustic feedback in flows such as supersonic screeching jets. The process by which energy is transferred from incident sound waves into hydrodynamic instabilities in a flow is called *receptivity*. Understanding of the receptivity process also opens the possibility of active control of shear flows using sound. Existing receptivity theories are restricted to low temporal frequencies and linear (small) disturbances. The objective of this research is to explore mixing layer receptivity outside of these parameter limitations using a computational approach.

Figure 6 shows a schematic of the present computational model problem. A thin splitter plate separates two streams of fluid which form a mixing layer downstream of the plate trailing edge. Incident acoustic waves scatter at the trailing edge, creating instability waves which grow exponentially downstream until nonlinear processes lead to vortex roll-up in the mixing layer. Figure 7 shows an example of the instantanous picture of the computed acoustic field with superimposed contours of vorticity. The mixing layer is supersonic ($M_1 = 1.2$), and the incident sound field consists of nonlinear plane acoustic waves with an associated disturbance pressure which is one percent of the ambient pressure. A complex wave pattern is observed downstream of the splitter plate, where sound waves have scattered from the vortices which have formed in the mixing layer. Quantitive data from this type of simulation allowed us to characterize the receptivity of this flow when the sound is very loud and the assumption of linearity may not hold. This simulation was performed on a grid with dimensions 1600 x 500, and required about 90 hours of wall clock time using 20 processors of the DURIP computing cluster. Details of the numerical method may be found in Barone and Lele (2002a) and results of further computations were reported in Barone and Lele (2002b).

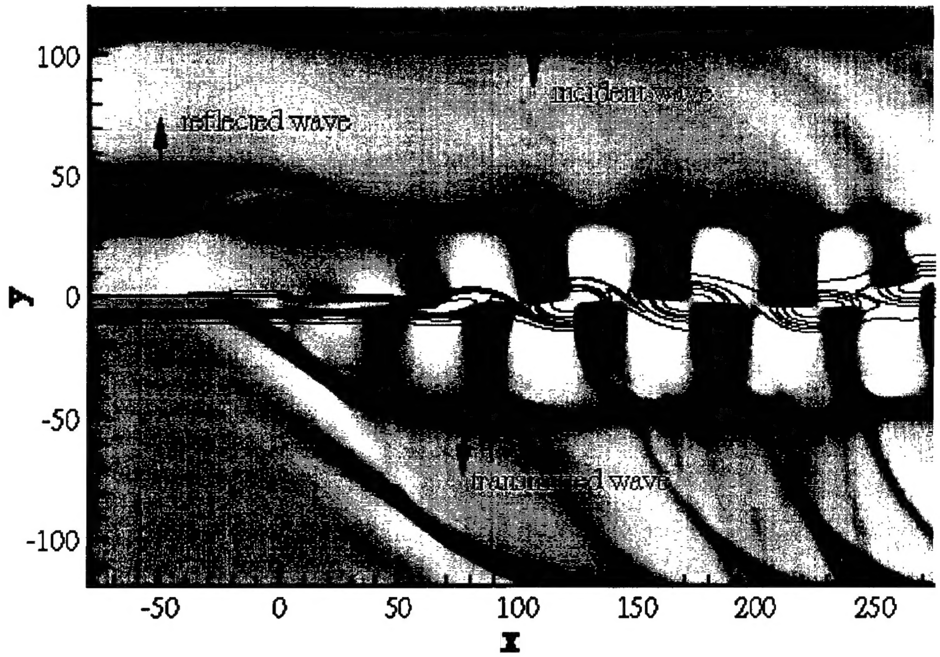

Figure 7: Calculation of the nonlinear receptivity of a supersonic mixing layer. The grey scale contours are dilatation; the red contours are vorticity.

Acknowledgments/Disclaimer

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Personnel

Cluster maintenance and system administration duties are handled by Daniel Bodony and Matthew Barone; both are doctoral degree candidates in the Dept. of Aeronautics and Astronautics at Stanford University.

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